Evidence for "Propeller" Effects In X-ray Pulsars GX 1+4 And GRO J1744-28

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ABSTRACT

We present observational evidence for "propeller" effects in two X–ray pulsars, GX 1+4 and GRO J1744–28. Both sources were monitored regularly by the *Rossi X–ray Timing Explorer* (RXTE) throughout a decaying period in the X–ray brightness. Quite remarkably, strong X–ray pulsation became unmeasurable when total X–ray flux had dropped below a certain threshold. Such a phenomenon is a clear indication of the propeller effects which take place when pulsar magnetosphere grows beyond the co-rotation radius as a result of the decrease in mass accretion rate and centrifugal force prevents accreting matter from reaching the magnetic poles. The entire process should simply reverse as the accretion rate increases. Indeed, steady X–ray pulsation was reestablished as the sources emerged from the non-pulsating faint state. These data allow us to directly derive the surface polar magnetic field strength for both pulsars: 3.1×10^{13} G for GX 1+4 and 2.4×10^{11} G for GRO J1744-28. The results are likely to be accurate to within a factor of 2, with the total uncertainty dominated by the uncertainty in estimating the distances to the sources. Possible mechanisms for the persistent emission observed in the faint state are discussed in light of the extreme magnetic properties of the sources.

Subject headings: accretion, accretion disks — stars: pulsars: individual (GX 1+4, GRO J1744-28) — X-rays: stars

1. Introduction

In accreting X–ray pulsars, the strong magnetic field disrupts accretion flow at several hundred neutron star radii and funnels material onto the magnetic poles (e.g., Pringle & Rees 1972; Lamb, Pethick, & Pines 1973). X–ray emission mostly comes from the "hot spots" formed around one or both poles. Such emission is beamed (Basko & Sunyaev 1976) and thus produces X–ray pulsation by periodically passing through the line of sight as the neutron star rotates, if the magnetic and rotation axes of the neutron star are misaligned.

The strength of the magnetic field in X–ray pulsars can be illustrated by the size of the magnetosphere, which co-rotates with the neutron star. In the process of mass accretion, the ram

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pressure of the flow is exerted on the magnetosphere and is balanced by the magnetic pressure. Therefore, the magnetospheric radius is determined not only by field strength but also by mass accretion rate. In a bright state, the accretion rate is high, so the magnetosphere is usually small compared to the co-rotation radius at which the angular velocity of Keplerian motion is equal to that of the neutron star. Material is continuously channeled to magnetic poles, so the X–ray emission from "hot spots" pulsates persistently. As the accretion rate decreases, the ram pressure decreases, and thus the magnetosphere expands. As the magnetosphere grows beyond the co-rotation radius, centrifugal force prevents material from entering magnetosphere, and thus accretion onto magnetic poles ceases (Pringle & Rees 1972; Lamb, Pethick, & Pines 1973; Illarionov & Sunyaev 1975). Consequently, no X–ray pulsation is expected. This is commonly known as the "propeller" effect, because accreting matter is likely to be ejected in the presence of a strong magnetic field.

Although the propeller effects were predicted theoretically in the 1970's, there has been no direct observational evidence for them. If the "standard" pulsar theory is on the right track, such effects should be observable. A positive detection would not only confirm our understanding of X–ray pulsars but would also allow a direct determination of magnetic field strength in these systems. In this *Letter*, we report the discovery of such effects in two X–ray pulsars, GX 1+4 and GRO J1744-28, based on the RXTE observations.

GX 1+4 is a 2 minute pulsar with a low-mass M giant companion. It is highly variable in X-rays. The observed X-ray flux can vary by 2 orders of magnitude on a time scale of months. It has the hardest X-ray spectrum among known X-ray pulsars. Secular spin-ups and spin-downs have been observed at nearly equal rates (see Chakrabarty et al. 1997, and references therein). It has been, therefore, postulated that GX 1+4 is near spin equilibrium. Then, according to the "standard" model (Ghosh & Lamb 1979), the observed spin-down rate would require a surface magnetic field of a few $\times 10^{13}$ G. Hints for such an unusually strong magnetic field are also provided by the observed hard X–ray spectrum.

GRO J1744-28 is a transient X-ray pulsar with a period of 0.467 s and is thought to have a low-mass companion. It is the only known X–ray pulsar that also produces X–ray bursts and only the second source, after the Rapid Burster, that displays type II bursts (Lewin et al. 1996). The Rapid burster apparently only has a weak magnetic field. By analogy, GRO J1744-28 may also be a weakly magnetized system, but a strong enough field to be an X–ray pulsar.

2. Observations and Analysis

Both GX 1+4 and GRO J1744-28 were monitored regularly by *RXTE* in 1996. For this study, we only use data from the *Proportional Counter Array* (PCA). The PCA consists of five nearly identical large area proportional counter units (PCUs). It has a total collecting area of about 6500 cm^2, but for a specific observation some PCUs (up to two) may be turned off for safety reasons.

It covers an energy range from 2-60 keV with a moderate energy resolution ($\sim 18\%$ at 6 keV). Mechanical collimators are used to limit the field of view to a $1°$ FWHM.

2.1. X–ray Light Curves

Starting on 1997 February 17, GX 1+4 was observed roughly monthly by the PCA for $\sim$10 ks for each observation. Initially, it was in a relatively bright state, $\sim$100 mCrab, with a large pulse fraction ($\sim$60%). The X–ray brightness decayed steadily since that measurement, with the pulse fraction remaining roughly constant. By 1996 September 25, it appeared only as a $\sim$2 mCrab source. Importantly, the X–ray pulsation was not measured by using standard techniques such as fast Fourier transformation and epoch-folding (using a detection threshold of 3σ). For a better coverage of the source during this interesting period, we chose to observe it weekly for $\sim$5 ks each. GX 1+4 remained in this faint state (Chakrabarty, Finger, & Prince 1996; Cui & Chakrabarty 1996) until around 1996 November 29, when it brightened up and the pulsation was again detected (Wilson & Chakrabarty 1997). Unfortunately, no PCA coverage was possible for more than 2 months around this time because the Sun was too close to the source. Figure 1 summaries the X–ray flux history. Pulse-period folded light curves were obtained from the Standard2 data with a 16 s time resolution. From the folded light curves, we then computed the average pulse fraction, which is defined as the ratio of the difference between the maximum and minimum count rates to the maximum rate. The results are also shown in Fig. 1. Note that no pulsation is detected above 3σ in the faint state, so for each observation the light curve is folded around a period that maximizes the residual.

An extensive monitoring campaign on GRO J1744-28 started shortly after its discovery (Giles et al. 1996). At the beginning, GRO J1744-28 was observed weekly. It appeared as a $\sim$2 Crab persistent source with giant type II bursts (at more than 10 Crab). The sampling rate increased quickly to almost once per day when the source became fainter toward the end of April. By 1996 May 12, GRO J1744-28 entered a period when the X–ray pulsation was only detected intermittently with significance no more than 6σ. The persistent emission flux was about 50 mCrab. Such a faint state lasted for about 7 weeks. For this study, we have selected 13 observations to cover the entire period. In the same way as in Figure 1, the measured X–ray flux and average pulse fraction are shown in Figure 2 for GRO J1744-28 (with the detected X–ray bursts removed). Here, the pulse fraction was derived from the Binned-mode data with a 16-ms time resolution, except for the last observation where the Binned-mode data were not available and the Event-mode data with higher time resolution were used instead.

2.2. Spectral Characteristics

To derive the total X–ray flux, we modeled the observed spectra with a cut-off power law, which is typical of accreting X–ray pulsars (White, Swank, & Holt 1983). For both sources, a Gaussian component is needed to mimic an iron K_α line at $\sim$6.4 keV. Such a model fits the observed X–ray spectra of GX 1+4 reasonably well, with reduced χ^2 values in the range of 1-3, except for the first two observations, for which the object was relatively bright. Similarly, for GRO J1744-28, the spectra for the faint state can be fit fairly well by this simple model, although none of the results are formally acceptable in terms of reduced χ^2 values for the data for which the source was relatively bright. By examining the residuals, we found that the significant deviation mostly resides at the very low energy end of the PCA range, where the PCA calibration is less certain. Therefore, the flux determination should not be very sensitive to such deviation for these hard X–ray sources. Note that we did not follow the usual practice of adding systematic uncertainties to the data in the spectral analysis, because it is still not clear how to correctly estimate the magnitude of those uncertainties at different energies. The uncertainty in the flux measurement (as shown in Figures 1 and 2) was derived by comparing the results from different PCUs.

The observed spectrum varies significantly for GX 1+4. The photon index varies in the range of 0.4-1.7, and infered hydrogen column density, in the range of 4 to 15×10^{22} cm^{-2}, although the latter is poorly constrained in the faint state. The spectral cutoff occurs at 6-17 keV, with an e-folding energy in the range 11-55 keV. As GX 1+4 approaches the faint state, the spectrum becomes harder; eventually the spectral cutoff becomes unmeasurable. An opposite trend is observed for GRO J1744-28; its spectrum changes only mildly. When it was relatively bright, the photon index is steady (1.3-1.4) and the column density is in the range $3-5\times10^{22}$ cm^{-2}. The spectrum is cut off at 16-18 keV, with an e-folding energy in the range 11-19 keV. However, as it enters the faint state, the spectrum turns significantly softer: the photon index varies from 1.5 to 2.5 and the cutoff energy moves down to 5-8 keV with the e-folding energy in the range 15-26 keV. It is interesting to note that the harder spectrum completely recovers when the source brightens up again (as typified by the last observation in Fig. 2).

2.3. Magnetic Field

The absence of the X–ray pulsation when the pulsars were in a low brightness state is a clear indication of propeller effects. For pulsars, the co-rotation radius, r_{co}, is derived by equating the Keplerian velocity to the co-rotating Keplerian velocity, i.e., $\Omega r_{co} = (GM/r_{co})^{1/2}$, where Ω is the angular velocity of the neutron star, and M is the mass. Therefore,

$$r_{co} = 1.7 \times 10^8 \ P^{2/3} \left(\frac{M}{1.4M_\odot} \right)^{1/3} \ cm \tag{1}$$

where P is the neutron star spin period.

In the presence of an accretion disk, it is still uncertain how to determine the outer boundary of the magnetosphere in a pulsar (e.g., Ghosh & Lamb 1979; Arons 1993; Ostriker & Shu 1995; Wang 1996. To a good approximation, here we define the magnetospheric radius, r_m, as where the magnetic pressure balances the ram pressure of a spherically accretion flow. Assuming a dipole field at large distance from the neutron star, we have (Lamb, Pethick, & Pines 1973)

$$r_m = 2.7 \times 10^8 \ \left(\frac{L_x}{10^{37} \ erg \ s^{-1}} \right)^{-2/7} \left(\frac{M}{1.4M_\odot} \right)^{1/7} \left(\frac{B}{10^{12} \ G} \right)^{4/7} \left(\frac{R}{10^6 \ cm} \right)^{10/7} \ cm, \qquad (2)$$

where L_x is the bolometric X-ray luminosity, B is the surface polar magnetic field strength, and R is the neutron star radius.

The mass accretion onto the pulsar magnetic poles ceases when $r_{co} = r_m$. From equations (1) and (2), the magnetic field strength is given by

$$B = 4.8 \times 10^{10} \ P^{7/6} \left(\frac{F_x}{1.0 \times 10^{-9} \ erg \ cm^{-2} \ s^{-1}} \right)^{1/2} \left(\frac{d}{1 \ kpc} \right) \left(\frac{M}{1.4M_\odot} \right)^{1/3} \left(\frac{R}{10^6 \ cm} \right)^{-5/2} \ G \ (3)$$

where F_x is the minimum bolometric X-ray flux at which X–ray pulsation is still detectable, and d is the distance to the source.

For GX 1+4 and GRO J1744-28, the observed 2-60 keV X-ray fluxes are ~ 0.16 and $2.34 \times 10^{-9} \ erg \ cm^{-2} \ s^{-1}$, respectively, when the X–ray pulsation becomes unmeasurable. Correction to the measured 2-60 keV flux at both high and low energies needs to be made in order to derive the bolometric X–ray flux. Because of the spectral cutoff, little flux is expected from above 60 keV for GRO J1744-28. At the low energy end (< 2 keV), extending the power law (with a photon index of about 1.5) does not add much flux either ($< 18\%$). The correction for absorption yields less than 30%. Therefore, the uncertainty lies primarily in the distance measurement which can only vary by a factor of 2 (Giles et al. 1996). Assuming a distance of 8 kpc (Giles et al. 1996), $B \simeq 2.4 \times 10^{11}$ G. Similarly, for GX 1+4, the bolometric correction below 2 keV is small. At high energies, no spectral cutoff is observed in the faint state, so it must be beyond the PCA passing band. At the beginning of the faint state, the observed photon index is ~ 1.7, so it is highly unlikely that the bolometric flux is more than a factor of 2 higher than what is measured (requiring a cutoff energy of ~ 300 keV). However, the spectrum seems to harden in the faint state, and the photon index can drop as low as 0.5. Even so, a spectral cutoff at ~ 100 keV would be required for a 100% bolometric correction above 60 keV. Assuming a distance of 6 kpc (which can vary by no more than a factor of 2; Chakrabarty & Roche 1997) and using the measured 2-60 keV flux in equation (3), we have $B \gtrsim 3.1 \times 10^{13}$ G for GX 1+4. In conclusion, the derived magnetic-field values are likely to be accurate to within a factor of two for both sources, and the total uncertainty is dominated by the uncertainty in estimating the distances.

3.   Discussion

What is the origin of the persistent emission in the faint state? The different (nearly opposite) spectral characteristics strongly suggest different emission mechanisms for GX 1+4 and GRO J1744-28. GX 1+4 has an M-giant companion star, and a relatively dense, slow stellar wind is expected in the system(Chakrabarty & Roche 1997). In fact, the comparable spin-up and spin-down rates observed seems to suggest the presence of a retrograde accretion disk during the spin-down period (Chakrabarty et al. 1997), which is only possible in a wind-fed system (as opposed to the Roche lobe overflow system). Because GX 1+4 has a strong magnetic field, accreting matter may not be able to penetrate the field lines very much and is likely to be flung away at a very high velocity. The velocity can be roughly estimated as $v \simeq (2GM/r_{co})^{1/2}$ (Illarionov & Sunyaev 1975), which is $\sim$2000 km/s. As the material plows through the dense stellar wind at such a high velocity, a shock is bound to form. The observed emission in the faint state may simply be the synchrotron radiation by relativistic particles accelerated by the shock through mechanisms like Fermi acceleration (Fermi 1949). The nonthermal nature of such emission is consistent with the disappearance of the spectral cutoff in the faint state. This emission mechanism is thought to be responsible for the unpulsed X–ray emission observed from the Be binary pulsar system PSR B1259-63 near periastron (Grove et al. 1995).

For GRO J1744-28, the magnetic field is very weak for an X–ray pulsar. When the propeller effects take place, a significant amount of accreting material might leak through "between the field lines" and reach the neutron star surface (Arons & Lea 1980). The observed emission in the faint state would then come from a large portion of the surface and so would not be pulsed. The surface temperature reached is expected to be lower than that of the hot spots; thus the spectrum is softer, which is consistent with the observation.

However, both sources are in the Galactic center region, so source confusion could be a serious problem. It is natural to question whether we actually detected the sources when the X–ray pulsation was not seen. We have carefully searched the catalogs for known X-ray sources within a $1°$ radius circle around each source. None are found around GX 1+4. Moreover, the iron line at $\sim$6.4 keV is particularly prominent in GX 1+4 (see Fig. 3). Its presence and distinct shape with respect to the continuum greatly boosted our confidence about detection of the object in the faint state. GRO J1744-28 was still fairly bright ($\sim$50 mCrab) even in the faint state. Eighteen known X–ray sources appeared within the search circle, six of which can be brighter than 30 mCrab, but only GS 1741.2-2859 and A 1742-289 are potentially close enough to the PCA pointing direction ($< 30'$) and bright enough to contribute significantly to the observed counts. However, both are X–ray transients, and are currently off, according to the nearly continuous monitoring with the All-Sky Monitor (ASM) aboard *RXTE*. An extensive search for potential new sources in the region was also made with the ASM, but yielded null detection. The ASM long-term light curve indicates that GRO J1744-28 was on throughout the faint state. In fact, type II X–ray bursts were detected again by the PCA during the later part of this period.

We seem to have selected two X–ray pulsars with their magnetic properties at opposite extremes. Both experience a period when the mass accretion from the companion star is hindered by the centrifugal barrier. The inferred magnetic field strength is in line with our previous knowledge about both sources. These results are important in constraining the details of the theoretical models on the X–ray emission mechanisms and thus will help us complete the pictures on these sources, especially GRO J1744-28, an unexpected bursting X–ray pulsar. It should be noted that the derived dipole field strength for GRO J1744-28 is consistent with the reported upper limits (Finger et al. 1996; Daumerie et al. 1996; Bildsten & Brown 1997) but is larger than the value derived from the observed 40 Hz QPO (Sturner & Dermer 1996), based on the assumption that the "beat frequency model" of Alpar & Shaham (1985) applies. This model is, however, inconsistent with the observed dependence of the QPO properties on the X-ray brightness of the source (Zhang et al. 1996).

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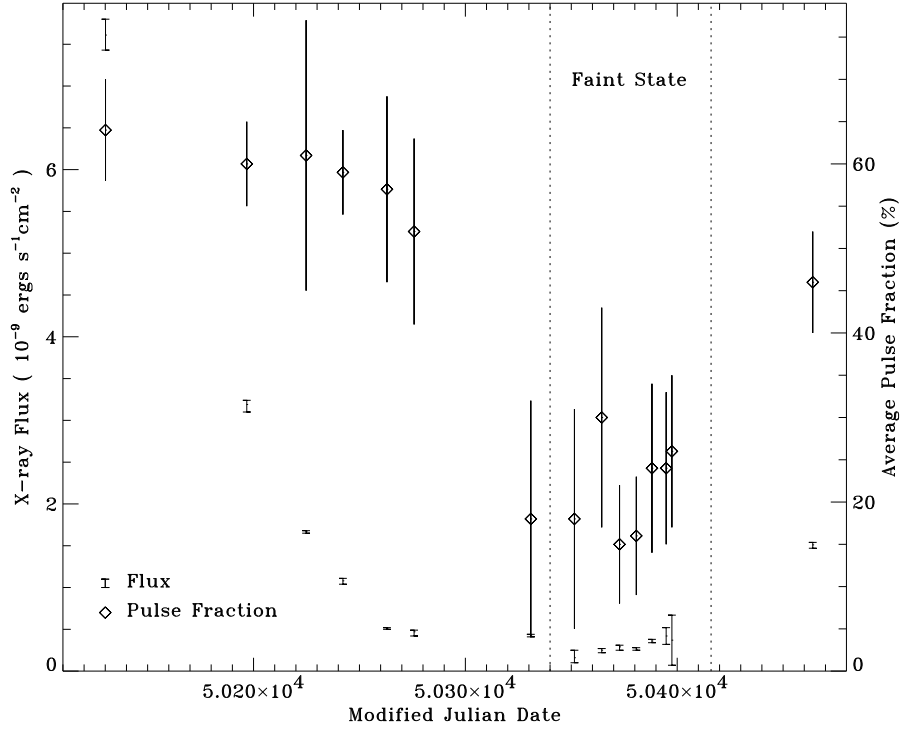
Fig. 1.— X-ray flux and pulse fraction of GX 1+4. The fluxes were derived in the 2-60 keV band. Upper and lower limits are shown, representing the range of the flux measurements from different PCUs. See text for a definition of the pulse fraction. The error bars on the pulse fraction represent mean standard deviation. The time period between two dotted lines indicates the faint state when the X–ray pulsation was not detected. The left bound is only meant to indicate that it started some time between the two closest PCA observations. The right bound is from the BATSE monitoring of the source (Wilson & Chakrabarty 1996). MJD 50351 corresponds to 25 September 1996.
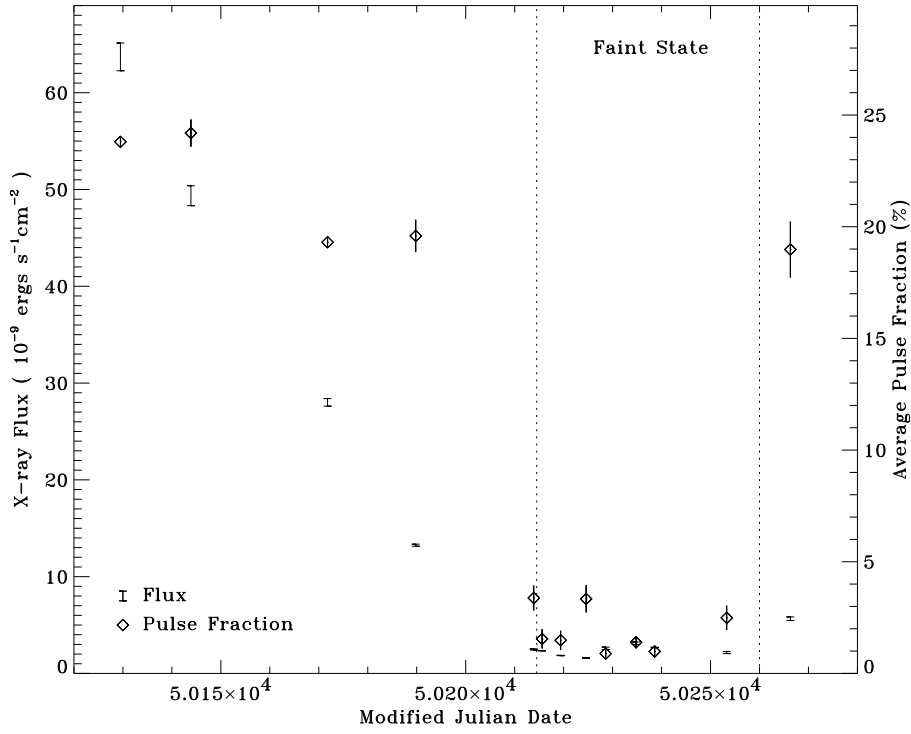
Fig. 2.— The same as Figure 1, for GRO J1744-28. In this case, the pulsation was only intermittently detected in the faint state. Again, the dashed lines are drawn arbitrarily between two adjacent PCA observations.
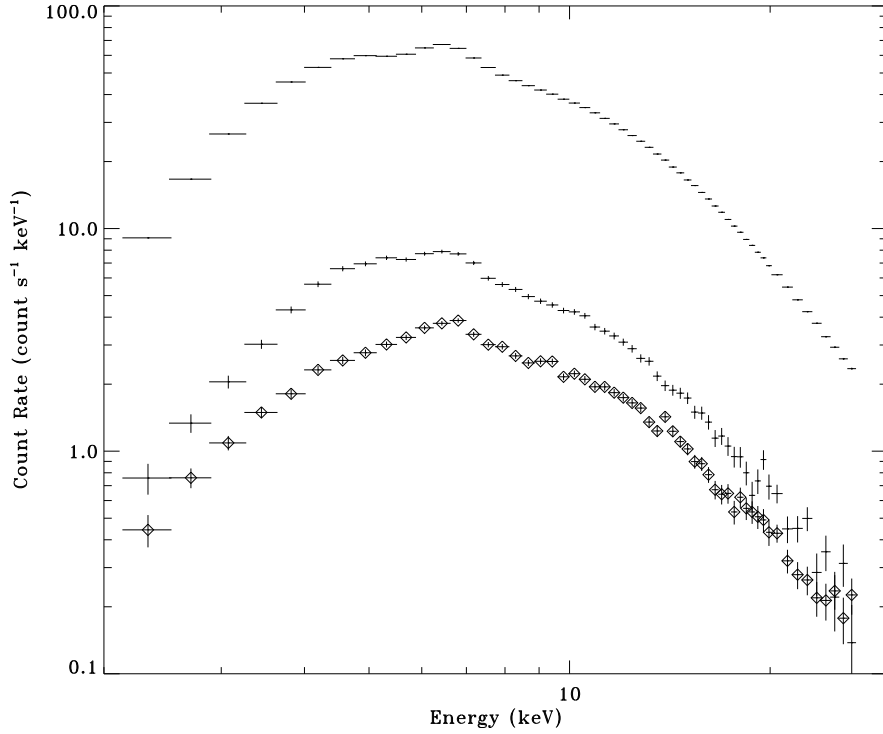
Fig. 3.— Selected X–ray spectra of GX 1+4. The upper curve is derived from the 4/23/96 observation (MJD 50196.8), and is typical of the source when it is relatively bright. The middle curve is from the 7/11/96 observation (MJD 50275.9), and the bottom one from the 10/8/96 observation (MJD 50364.4), which are meant to show typical X–ray spectra just before and after the pulsation became undetectable, respectively. Note a strong iron line K_α at ∼6.4 keV in all cases.